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SPECTRAL STUDIES OF THE ELASTIC WAVE RADIATION FROM APPALACHIAN EARTHQUAKES AND EXPLOSIONS - EXPLOSION SOURCE SPECTRA MODELING USING BLASTER'S LOGS

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13. ABSTRACT (*Maximum 200 words*)
The objectives of this study are to model the observed spectra of seismic radiation from large industrial explosions using information obtained from blaster's logs and to compare the explosion spectra with those of small earthquakes occurring in the same source region. The data set consists of digital waveforms from four mining explosions (200,000+lbs of explosives each) and two earthquakes (M = 3.5,4.0) in eastern Kentucky. The data were recorded on a short-period regional network at distances ranging from 180 to 400 km and have good signal-to-noise ratios at frequencies from 0.5 to 10 Hz.

The explosion amplitude spectra were found to differ markedly from those of the earthquakes, by exhibiting strong time-independent amplitude modulations. This spectral modulation is shown to be directly attributable to the explosive charge geometry and detonation sequence employed, and is independent of source-station path and recording site.

Modeling of the explosion source spectra shows that the major contributor to the modulated character of the spectra are amplitude minima at frequencies related to the total duration of the explosion sequence. Another important effect is spectral

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reinforcement at low frequencies (e.g., 5 Hz) due to the comparatively long delay (0.2 sec) between the firing of individual rows of explosives. These features dominate both Pg and Lg amplitude spectra at frequencies less than 7 Hz. Accurate modeling of the observed spectra at frequencies greater than a few Hertz requires that the azimuth of the recording site be taken into account. Also, the spectra at higher frequencies become sensitive to random variations in the firing times of any of the various subexplosions.

CONTENTS

INTRODUCTION

The successful monitoring of smaller underground nuclear explosions at regional distances requires the ability to discriminate those tests from ordinary industrial explosions (mine and quarry blasts) and from natural earthquakes. Recent studies have demonstrated that the practice of delay or ripple firing commonly used for industrial explosions often produces observable modulations in the amplitude spectra of regional seismic signals that is not observed in earthquakes (Baumgardt and Ziegler, 1988; Smith, 1989; Hedlin et al, 1989; Baumgardt and Young, 1990; Hedlin et al, 1990). The form of the delay-fired explosion spectrum depends upon, among other factors, the physical layout of the charges, the charge sizes, the delay time intervals between the various individual explosion sequences and the azimuth of the recording station from the source. Because single event sources such as smaller earthquakes or nuclear tests tend not to produce modulated source spectra, the observation of significant spectral modulations could provide a useful discriminant. However, path and receiver effects may complicate the situation. For example, the spectra of the regional seismic phases Pn, Pg, Sn and Lg can be influenced by the structure of the crustal waveguide and the anelastic absorption process will diminish spectral enhancements at high frequencies. The resonance effects of near surface, low velocity material at the source and at the receiver also can, in principle, introduce spectral modulations.

In this study, we examine the spectra recorded at near regional distances from large surface mining explosions and compare them with theoretical spectra derived on the basis of information provided in the blaster's logbooks. Additionally, we compare the explosion signals with those of some small earthquakes in the same source region, featuring similar propagation paths to the recording stations. We study the cause of the observed modulations in the explosion spectra, the effect of different source-station propagation paths and site response on the spectra, and the spectral differences observed between the explosions and the earthquakes.

Data

The data set is derived from digital waveforms recorded by the Virginia Regional Seismic Network. Figure 1 shows the locations of the network stations, along with the locations of the four explosions and the epicenters of the two earthquakes employed in the study. The network utilizes 1 Hz seismometers. The analog seismic signals are transmitted to a central recording facility by FM telemetry and digitized at 100 samples/sec. The time series of these six events are shown in Figure 2, as recorded at station WMV.

Explosion Spectral Modulation

Generally, surface mine or quarry blasting operations employ explosive charges in holes that are arranged spatially in one or more rows. The individual charges are usually fired in a time sequence designed to achieve objectives such as proper rock breakage, reduction of fly rock and directed movement of the fractured rock mass away from the free face of the quarry. The time intervals (delays) between the individual subexplosions may be on the order of a few milliseconds to hundreds of milliseconds, depending on the application (Langefors and Kihlstrom, 1963; E.I. du Pont de Nemours & Co., 1978). For large mining explosions similar to those studied here, a variety of different delays may be employed.

Baumgardt and Ziegler (1988), Smith (1989) and Hedlin et al (1990) discuss the origin of spectral modulations in regional seismograms of industrial explosions. Assuming that the explosion source-time function is a linear superposition of individual subexplosions (Stump and Reinke, 1988), we can model the explosion source by convolving a source wavelet S(t) with an impulse series W(t). In addition to the firing times of the subexplosions, W(t) must also incorporate the spatial distribution of the charge holes, the azimuth of the receiver and the wave velocity of the material. The source-time function, A(t), for an explosion with n subexplosions observed at distances large in comparison to the dimension of the charge layout, is given by

$$A(t) = S(t) * W(t), \qquad (1)$$

where $$W(t) = \sum_{j=1}^{n} \alpha_j \delta(t - \tau_j'), \tag{2}$$

and $$\tau_j' = \tau_j - (x_j \sin\theta + y_j \cos\theta)/V. \tag{3}$$

Here, $\delta(t)$ is the Dirac delta function, τ_j is the time of the j'th subexplosion defined relative to the time of the initial subexplosion, x_j and y_j are the coordinates of the j'th subexplosion in a coordinate system with origin at the location of the initial subexplosion. The constant α_j represents the amplitude of the subexplosion. The azimuth θ from origin to recording station is measured clockwise from the Y axis and V is the phase velocity. The amplitude spectrum $A(\omega)$ of the source-time function is given by

$$A(\omega) = |S(\omega)W(\omega)|, \tag{4}$$

where $$W(\omega) = \sum_{j=1}^{n} \alpha_j \exp(i\omega\tau_j') \tag{5}$$

Consider a simple case where a row of 10 holes with equal charges is fired sequentially from one end with a constant delay $(\tau_j - \tau_{j-1})$ of 25 msec, resulting in an explosion of duration 0.25 sec (Figure 3). For simplicity, assume that $S(t) = \delta(t)$, and a hole spacing $(x_j - x_{j-1})$ of 4 meters and a velocity V of 3000 m/sec. The modulation of $A(\omega)$ in this case, regardless of station azimuth θ, involves two dominant effects. The first is amplitude reinforcement due to the constant time intervals (delays) between subexplosions. This reinforcement occurs at frequencies which are approximately integer multiples of the inverse delay interval. The second effect is spectral "scalloping," characterized by amplitude minima at frequencies given approximately by integer multiples of the inverse duration of the explosion sequence. In the case for θ=0 deg, the resulting spectrum is exactly that of the delay time series, with spectral reinforcements at 0, 40, 80 ... Hz, and spectral minima at 4, 8, 12 ... Hz (Figure 3). For θ=90 deg, the apparent delays between the explosions (as seen from the station) are shortened by a Doppler-like effect, due to the progression of the shotpoint in the direction of the receiver, and the finite wave velocity. Hence, the spectral reinforcements and minima appear at higher frequencies (Figure 4, top). The opposite effect happens for a receiver on an azimuth in the opposite direction: the reinforcements and spectral minima are shifted to lower frequencies. In actual practice, there may be significant variation in individual delay times, due to variations in the lengths and firing rates of detonating cords and blasting caps. This type of variation serves to reduce the amplitudes of the higher frequency reinforcement harmonics, and effectively "fills in" the spectral minima. Figure 4 (bottom) shows the spectrum resulting from the previous case (θ= 0 deg) when a random error with zero mean and standard deviation equal to 10% of the mean delay time is added to the times of the subexplosions. This "whitens" the spectrum by reducing the amplitude of the high frequency peak at 80 Hz and filling up the high frequency minima. Note that the effect of station azimuth and random variation of firing times is minimal for the low frequency part of the spectrum.

Real explosions often incorporate multiple rows of charge holes which may be "decked" (i.e., separate delays for upper and lower parts of a single hole). The firing of multiple rows is generally done sequentially, with relatively large delays between rows so as to allow time for the fractured rock mass to move away from the newly created free face. These row delays may produce important amplitude reinforcements at relatively low frequencies. Figure 5 shows the time series for a case where four rows of 10 holes each are fired with 0.11 sec delays between rows. Note, for example, that the second row's first hole is detonated just after the fifth hole of the first row. Thus the 0.11 sec delay between rows refers to the initiation times of each row of charges. As in the previous case, the delays between firings of adjacent holes in a row is 0.025 sec, and the azimuth θ is 0 deg. Figure 5 (bottom) also shows the resulting spectrum. The row delays produce additional amplitude reinforcements at n/0.11 Hz or 9.1, 18.2, 27.3 Hz... etc. The longer duration of the explosion sequence (0.58 sec) produces a "scalloping" effect with amplitude minima more closely spaced in frequency, compared to the previous case for a single row of charges.

Explosion Source Information

The explosions studied here were fired to remove the soil and rock overburden from coal seams. We obtained copies of the blaster's logs and have used the information contained therein to model the explosion source amplitude spectrum using equations 1 through 5.

The detail of information contained in the logs varied among the individual explosions. However, in all cases, the firing times of each charge could be ascertained. Other pertinent information contained in the logs included the distance between rows (burden) and between holes in a row (spacing), the types of millisecond delay connectors used (9,17,42 and 200 msec, in various combinations), the types of downhole delay blasting caps (450 or 500 msec), the total charge weight used for each hole and the maximum weight per delay period. Important ambiguities in the logs involve the distribution of charge weight within some of the decked holes for three of the four explosions: also, the detonation velocity of the surface and downhole detonating cord is not specified. All explosions were fired using detonating cord and millisecond delay connectors between holes. The main charge was a mixture of ammonium nitrate and fuel oil, initiated by a small primer charge using nonelectric downhole blasting caps. The copies of the blasting logs and other information, such as the orientation of the charge pattern with respect to North, were kindly furnished by the Kentucky Department of Mines and Minerals (written communication).

Explosion 1: 5/22/90

This explosion is well documented in the logbook, and the charge weight for each delay period is known. Figure 6 shows the charge pattern. It consisted of four rows of decked charges with the initiation point in the center of the row adjacent to the free face. The burden and spacing were 8.8 and 11 meters, respectively. The majority of delays used between holes in a given row were 17 msec, and each row was delayed 200 msec. The 56 charge holes were 31 cm in diameter and were drilled to a depth of 34.1 m. The lower part of each hole was loaded with 1877 lbs of explosive. The bottom charge was separated from the top charge of 2248 lbs of explosive by a 3 meter deck of drill cuttings. The top charge was fired using a 450 msec delay nonelectric cap: the bottom charge was delayed 50 msec by using a 500 msec nonelectric cap. Figure 6 shows the delay time series W(t) for a station azimuth of 307 deg.

Explosion 2: 6/12/90

This explosion consisted of five rows of charges and was more complex than Explosion 1, having an asymmetrical first row (Figure 7). This first row of 11 holes was loaded with 2885 lbs of explosives in 25 cm diameter holes drilled to 33.8 m. The remaining 84 holes were 31 cm in diameter and were loaded with 4642 lbs of explosives. All holes are assumed to be decked with upper and lower charges having downhole delays of 450 and 500 msec. Unfortunately, the logbook does not specify the charge weight distribution for upper and lower decks. Unannotated drawings in the logbook suggest equal weights for the decks in rows 1, 4 and 5. A weight ratio of 2/1 (upper/lower) is suggested for rows 2 and 3. Burden and spacing were 9.1 and 11.6 m, respectively.

Explosion 3: 7/9/90

This explosion consisted of 4 rows, fired sequentially from one end (Figure 8). Diameter and depth of the holes were 31 cm and 36 m. Burden and spacing were 9.1 and 11.6 m, respectively. Again, the log is not specific about the charge distribution between the upper and lower decks. For modeling, the specified weight of 4985 lbs per hole was distributed equally between the upper and lower decks in rows 3 and 4, and with a ratio of 3/1 (upper/lower) in rows 1 and 2, on the basis of unannotated drawings in the logbook.

Explosion 4: 9/7/90

This explosion involved 84 holes (31 cm X 37 m), each loaded with 4872 lbs of explosives. There is uncertainty as to whether or not the charges were decked for this explosion. The modeling was performed for both decked and undecked assumptions. For the decked explosion, an upper/lower charge weight ratio of 2/1 was assumed (Figure 9). Burden and spacing were 9.1 and 11.6 m, respectively.

Observed Explosion Spectra versus Theoretical

The explosions studied here produced time independent spectral modulations. This phenomenon has been noted previously (see, e.g., Baumgardt and Ziegler, 1988) from industrial explosions, and is an indication that the modulations are source related and not due to multipathing. It is most apparent when the data are displayed in a sonogram or time-frequency plot wherein the spectral content of the entire signal is plotted as a function of time.

Figure 10 shows a sonogram for Explosion 2. It was created using an approach similar to that of Hedlin et al (1989). Instrument corrected acceleration power spectra were computed using non-overlapping five second windows, for times beginning well before the signal onset and extending into the signal coda. The spectra were detrended and amplitude normalized by subtracting a second degree polynomial fitted by least squares to the logarithms of acceleration power. Noise correction was performed by contouring only those values which exceed the pre-signal noise levels by a factor of 5. Note that the spectral peaks persist throughout the signal, from P onset to well within the Lg coda.

In Figures 11 through 16, we compare the acceleration amplitude spectra of Lg and Pg with theoretical spectra for each of the four explosions. All spectra have been corrected for instrument response and anelastic attenuation. The assumed Pg and Lg quality factor is $Q=811f^{0.42}$ (Chapman and Rogers, 1989). As a preliminary, Figure 11 shows the Lg spectra recorded at WMV from Explosion 1, along with the pre-P noise background. Both spectra were calculated using 20 second time windows, and smoothed using a 4 point moving average filter. Note that the signal/noise ratio exceeds 2 at frequencies less than 15 Hz. This station, along with station VWV, gave the best signal/noise ratios for the explosions being studied.

Figure 12 shows the vertical component Lg acceleration spectrum (20 sec window) at stations WMV, VWV and CVL, in comparison with the theoretical source acceleration spectrum for Explosion 1. The observed spectra are plotted at frequencies where the signal/noise ratio exceeds 2. The theoretical model assumes a Brune (1970) ω^2 amplitude spectrum for the source wavelet: hence, in equation (4),

$$\left| S(\omega) \right| = \frac{\omega^2}{1+\left(\frac{\omega}{\omega_c}\right)^2} . \quad (6)$$

Trial and error modeling indicates a corner frequency of 3 Hz ($\omega_c=6\pi$) for Lg. The amplitude of the subexplosions are scaled in proportion to charge weight: i.e., α in equation (5) is charge weight in thousands of pounds. Note the good agreement between observed and theoretical spectra at frequencies less than about 7 Hz. The similarity of spectra at the three stations clearly demonstrates that the significant modulations at low frequency are path and site independent.

Various values for the phase velocity V were tested, and it was found that 3000 m/sec gave good agreement for the Lg spectrum. The lower frequency parts of the theoretical spectrum (less than 5 Hz) are insensitive to velocity V and station azimuth θ. However, these parameters become increasingly important at higher frequencies, and must be taken into consideration.

A potential for error in the modeling of the high frequency spectrum exists because of uncertainty involving the detonation velocity and arrangement of the surface and downhole detonating cord. In the case of all four explosions, it is assumed that the time delays introduced by the detonating cord have negligible effect on the amplitude spectra at the relatively low frequencies where we have adequate signal/noise ratios. Modeling of the effect shows little impact on the spectra at frequencies less than 20 Hz if the detonation velocity is in excess of 6000 m/sec.

Figure 13 shows the Pg acceleration spectrum from Explosion 1 at WMV, VWV and CVL. The Pg spectra were derived from 6 second time windows, and the spectra were smoothed with a 2 point moving average filter. Agreement between the Pg spectra and the model spectrum is not as good as for Lg. This may be due in part to the lower signal/noise ratios for Pg compared to Lg. Also, the Pg spectra appear to have more energy at high frequency (relative to low frequency energy) than do the Lg spectra shown in Figure 12. Hence, the theoretical spectrum was calculated using a source wavelet corner frequency of 10 Hz. The best fitting velocity was 5200 m/sec.

The Lg acceleration spectra for Explosions 2, 3 and 4 are shown in Figures 14 through 16. As in the previous example, the spectra were smoothed and plotted at frequencies where the signal/noise is greater than 2. Although the exact charge weight distribution is in question for these explosions, the overall shape and the frequencies of peaks and troughs in the observed spectra match those of the theoretical spectra well. Again, the theoretical Lg spectra source wavelet corner frequency is 3 Hz, and the velocity assumed is 3000 m/sec.

The appearance of the spectra from all four explosions at frequencies less than about 7 Hz is readily explained in terms of two effects. The most obvious aspect of the spectra are the amplitude minima at approximately 1.2, 2.3 and 3.4 Hz. These are directly related to the apparent duration of the explosion sequence and coincide with the amplitude nulls in the amplitude spectrum of a boxcar (square wave) time function of duration T sec. The frequencies of the amplitude nulls are given by n/T, where n=1,2,3,... etc. The apparent duration T of Explosions 1 through 4 are 0.90, 0.93, 0.85 and 0.84 seconds, respectively.

The other major aspect of the observed spectra is the persistent strong amplitude peak near 5 Hz. This peak is the result of reinforcement due to a nominal row delay of 0.2 sec used in all of the explosions.

Earthquake Spectra

Two small earthquakes which occurred in eastern Kentucky provide an opportunity to compare spectra from known explosions and earthquakes over similar source-station paths (Figure 1). Figures 17 and 18 show the amplitude spectra of unclipped portions of the Lg phase from the earthquakes. Comparison with Figures 12 through 16 indicates that the earthquake acceleration spectra are much flatter than the explosion spectra, exhibiting larger amplitudes at high frequency (>6 Hz) relative to low frequency amplitudes (<6 Hz). Examination of the earthquake sonograms (Figures 19 and 20) shows no evidence of time independent spectral modulation.

CONCLUSIONS

The surface mine explosions studied here produced signals at near regional distance featuring time independent spectral modulations of the type previously reported by Baumgardt and Ziegler (1988), Smith (1989), Hedlin et al (1989), Baumgardt and Young (1990) and Hedlin et al (1990). The dominant features of the modulation are independent of recording site and source-station path. In contrast, natural earthquakes which occurred in the mine locale exhibit much flatter acceleration spectra, with substantially larger high frequency amplitudes, and show no evidence of time independent spectral modulation.

The explosion spectra were successfully reproduced at low frequency using a simple source model. The most obvious characteristics of the explosion spectra are amplitude minima controlled by the total duration of the explosion sequence, and amplitude reinforcement due to relatively long (0.2 sec) delays between the firing of multiple rows of explosives. The model spectra at low frequency are relatively insensitive to station azimuth and phase velocity. However, as frequency increases, these parameters become important. Additionally, any random variation in the firing times of subexplosions strongly affects the high frequency spectrum. The agreement between the model Lg spectra and the observations is so good as to imply that for the study area at least, the Earth's transfer function for low frequency Lg waves is very simple: i.e., it acts primarily as an ideal low pass filter in terms of amplitude response.

The Pg and Lg explosion spectra show similar amplitude modulations. The Lg spectra more closely matched the model spectra, but this may be due to larger Lg signal/noise ratios. Interestingly, the Pg spectra appear to have relatively larger amplitudes at high frequency than do the Lg spectra. The Lg spectra suggest a source corner frequency of approximately 3 Hz for the individual subexplosions, whereas the Pg spectra corner frequency appears to be approximately 10 Hz. However, this observation may reflect some sort of path effect, not accounted for by the simple anelastic attenuation model we have used in comparing the observed spectra with the theoretical model.

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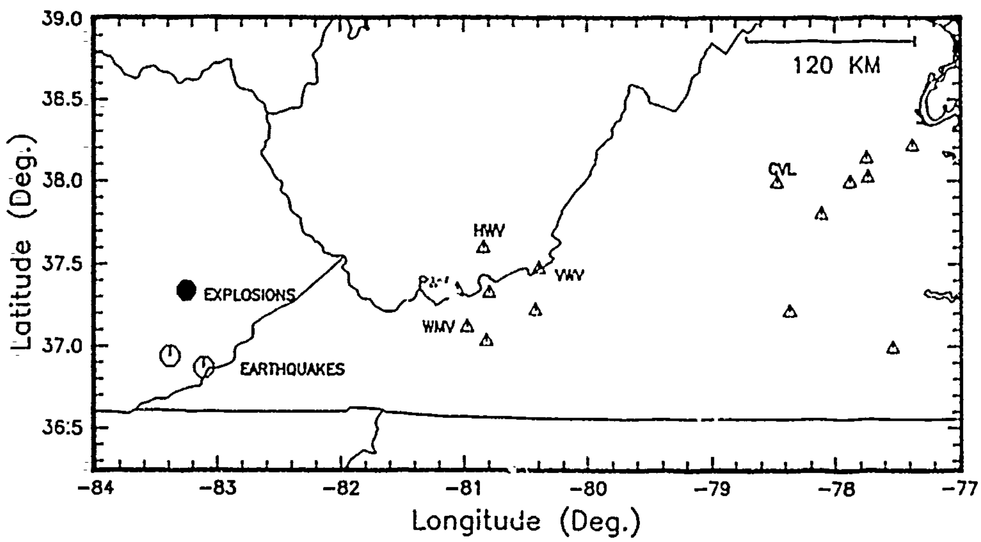


Figure 1: Location map showing network stations (open triangles) earthquake epicenters (open circles) and the location of four surface mine explosions (solid circle). Stations mentioned in the text are identified.

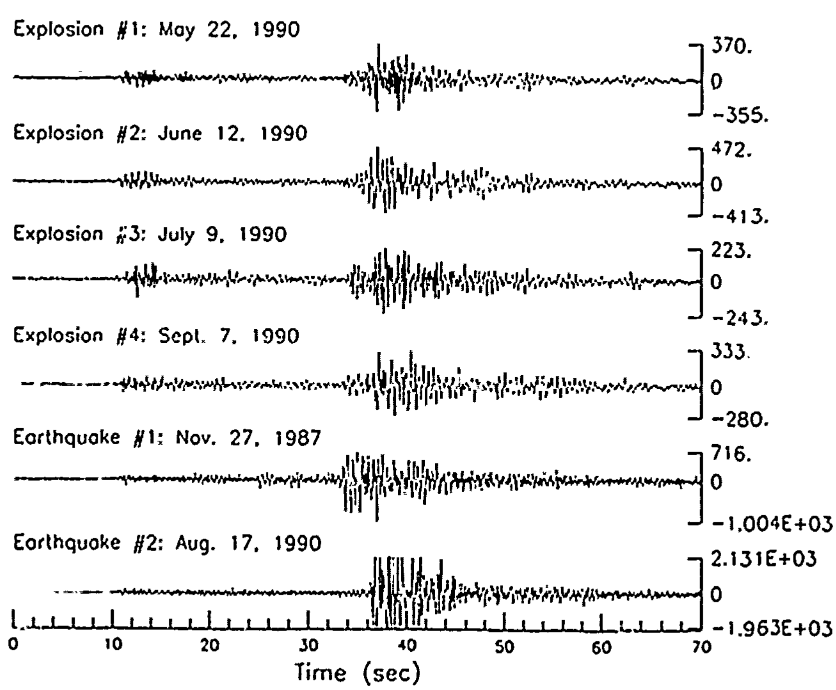


Figure 2: Vertical component seismograms from station WMV of the events involved in the study. Maximum and minimum trace amplitudes are shown on the right, in digital counts.

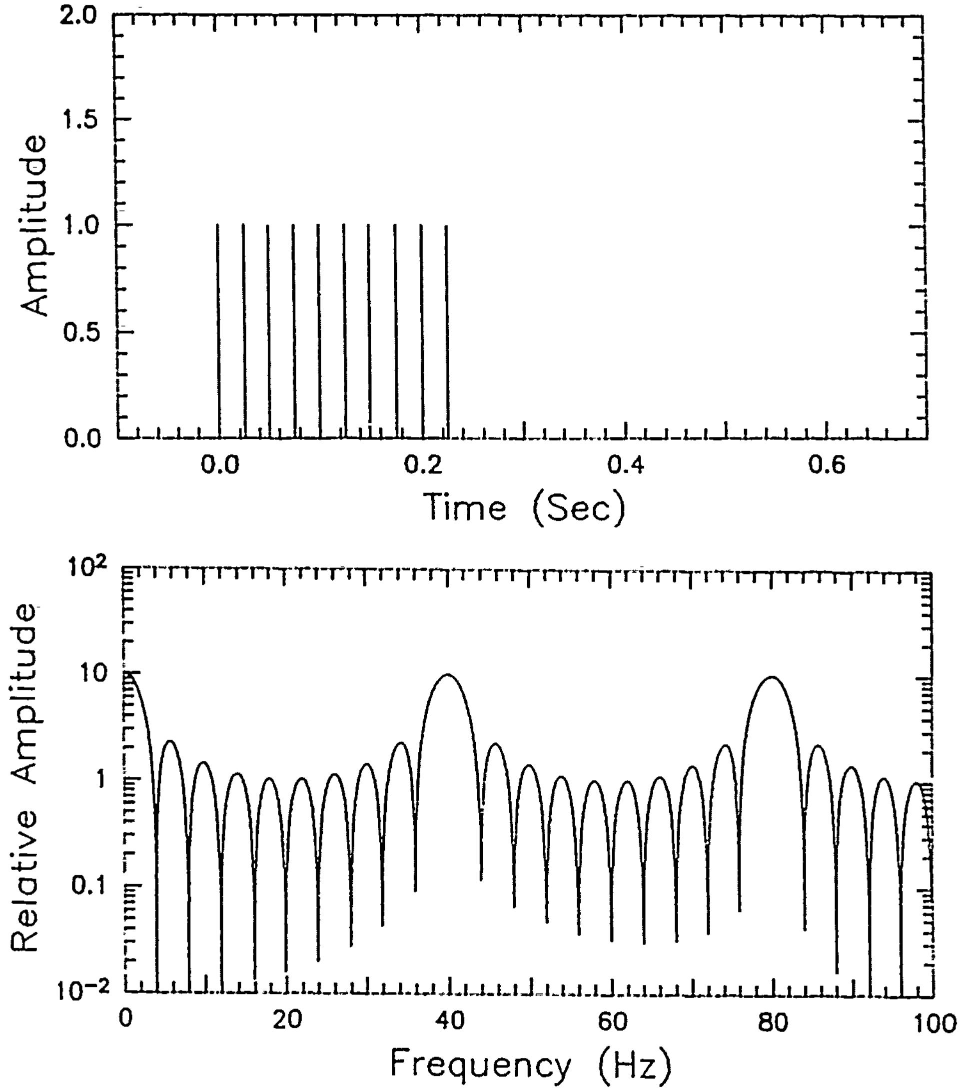


Figure 3: (Top) Time series of a single row of explosions, with station azimuth perpendicular to the row (θ=0 deg). (Bottom) Corresponding amplitude spectrum.

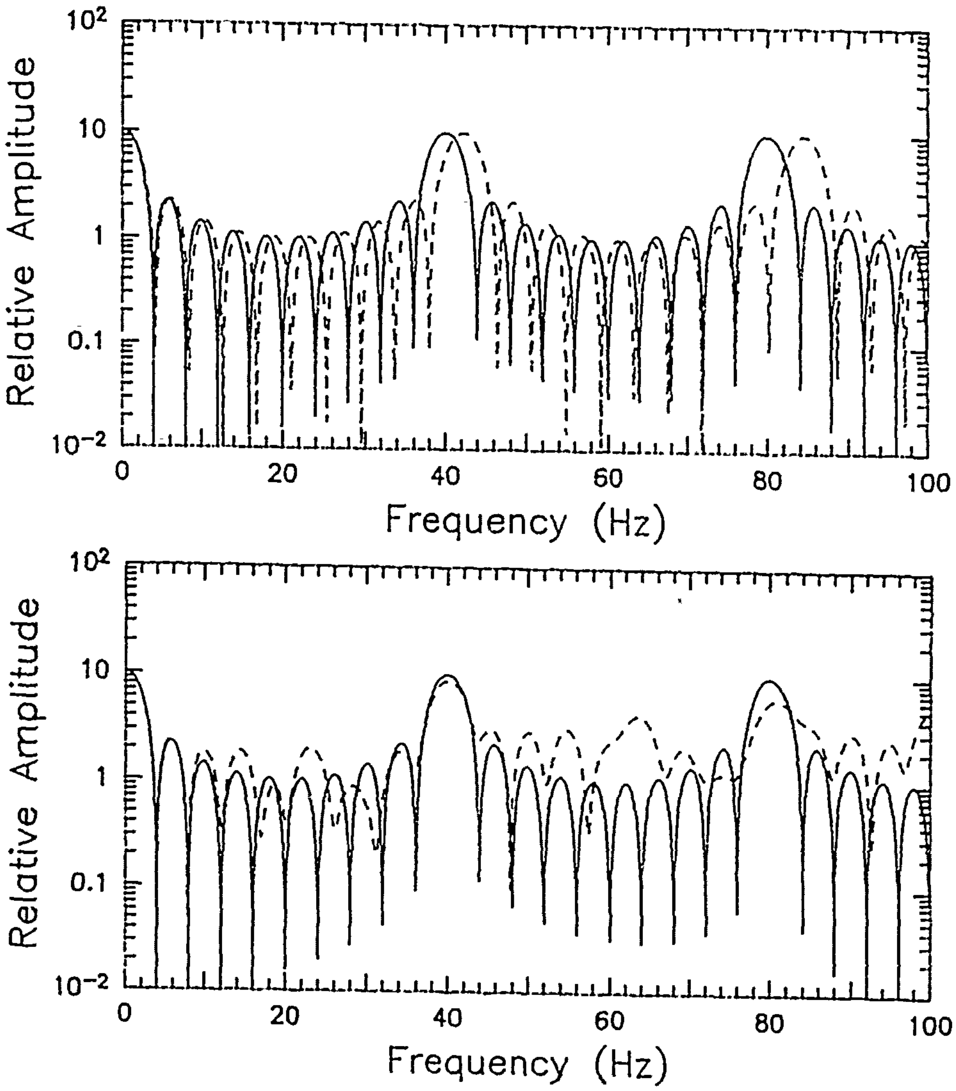
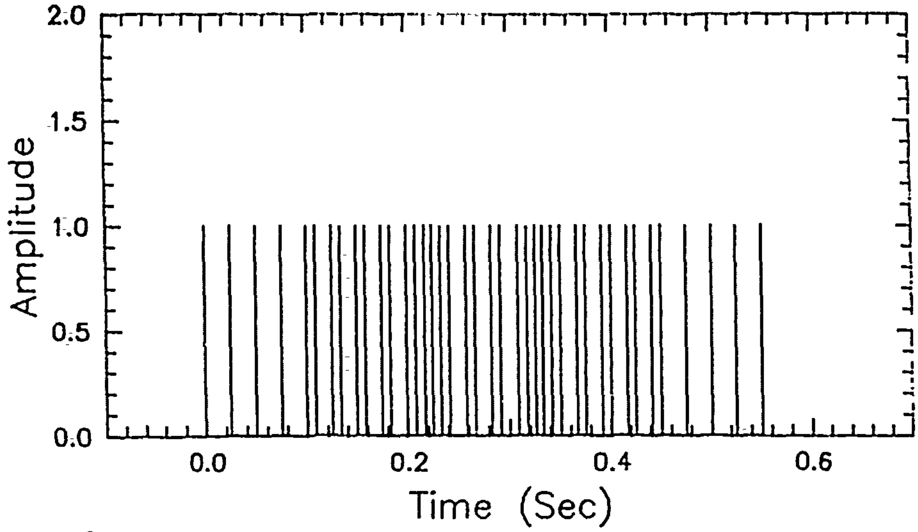


Figure 4: (Top) Dashed line shows spectrum corresponding to case where station azimuth is 90 deg. Solid line same as in Figure 3. (Bottom) Dashed line shows spectrum resulting from 10% random variation in delay times of individual explosions. Solid line same as Figure 3.



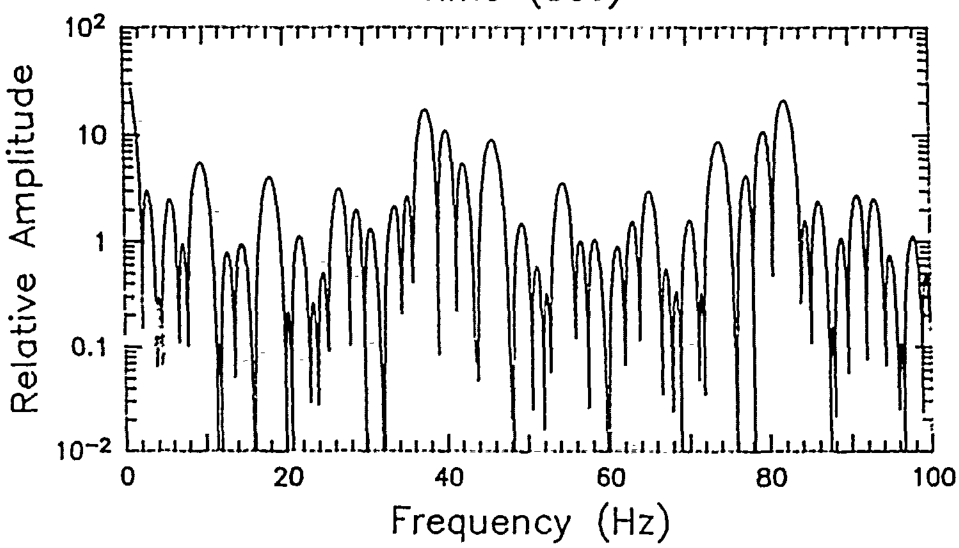


Figure 5:(Top) Time series for 4 rows of explosions with 10 charges per row: azimuth θ=0 deg, phase velocity V=3000 m/sec. (Bottom) Corresponding amplitude spectrum.

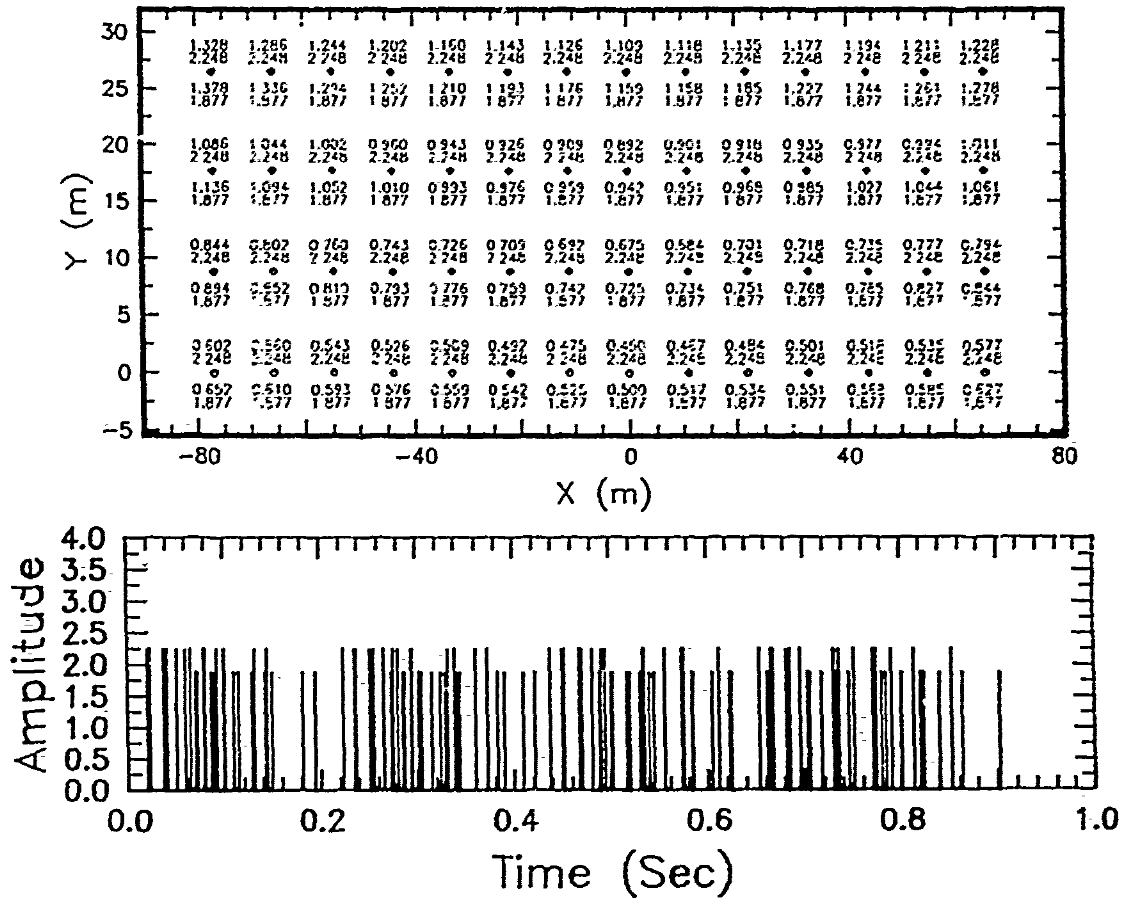


Figure 6: (Top) Charge pattern for Explosion 1 (plan view). Locations of each hole are indicated by small circles. Numbers above each circle indicate firing time (sec) of upper charge and charge weight (thousands of pounds), respectively. Numbers below circle refer to lower charge firing time and charge weight. (Bottom) Time series of Explosion 1, assuming station azimuth 307 deg, and phase velocity 3000 m/sec. Amplitude is charge weight in thousands of pounds.

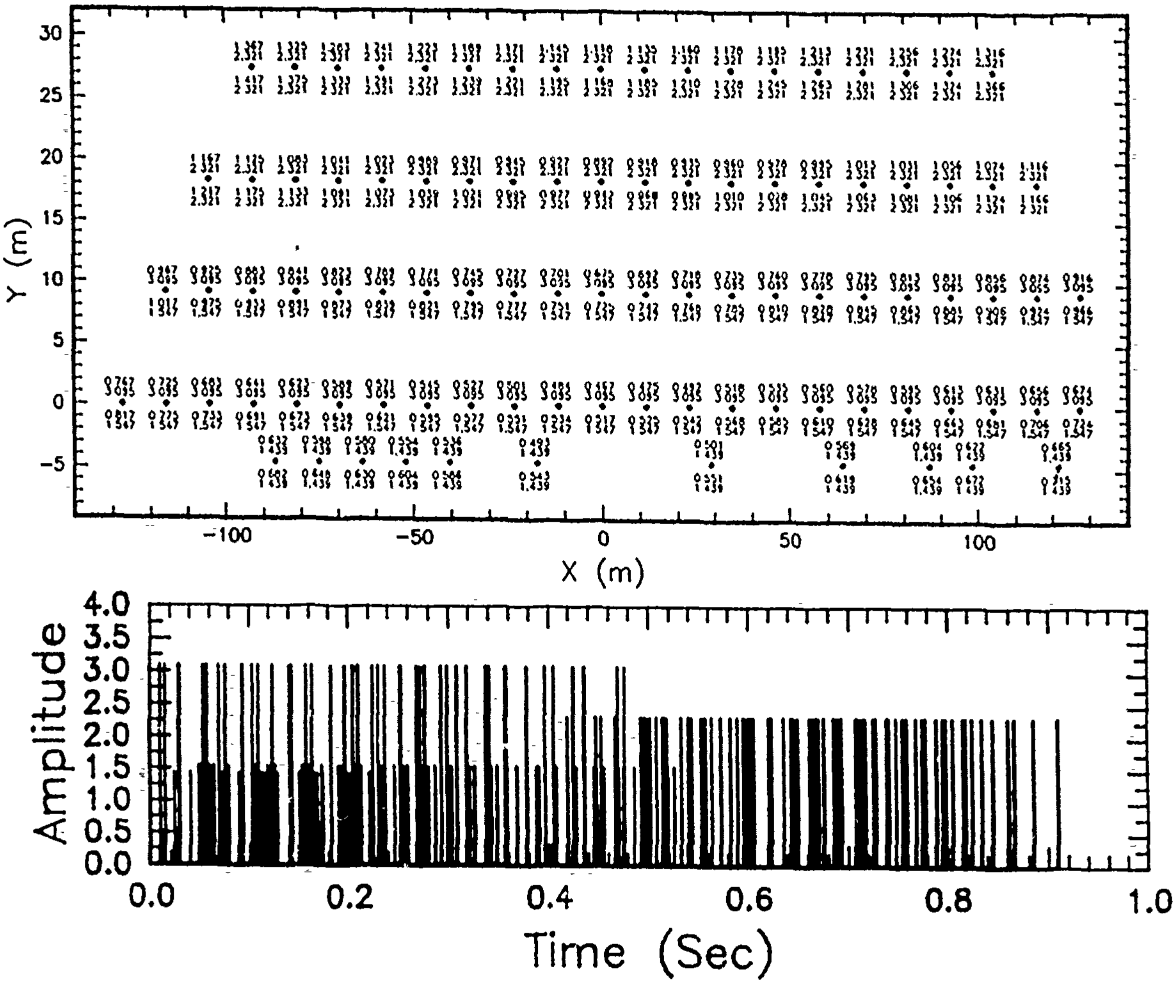


Figure 7: (Top) Charge pattern for Explosion 2 (plan view). Locations of each hole are indicated by small circles. Numbers above each circle indicate firing time (sec) of upper charge and charge weight (thousands of pounds), respectively. Numbers below circle refer to lower charge firing time and charge weight. (Bottom) Time series of Explosion 2, assuming station azimuth 327 deg, and phase velocity 3000 m/sec. Amplitude is charge weight in thousands of pounds.

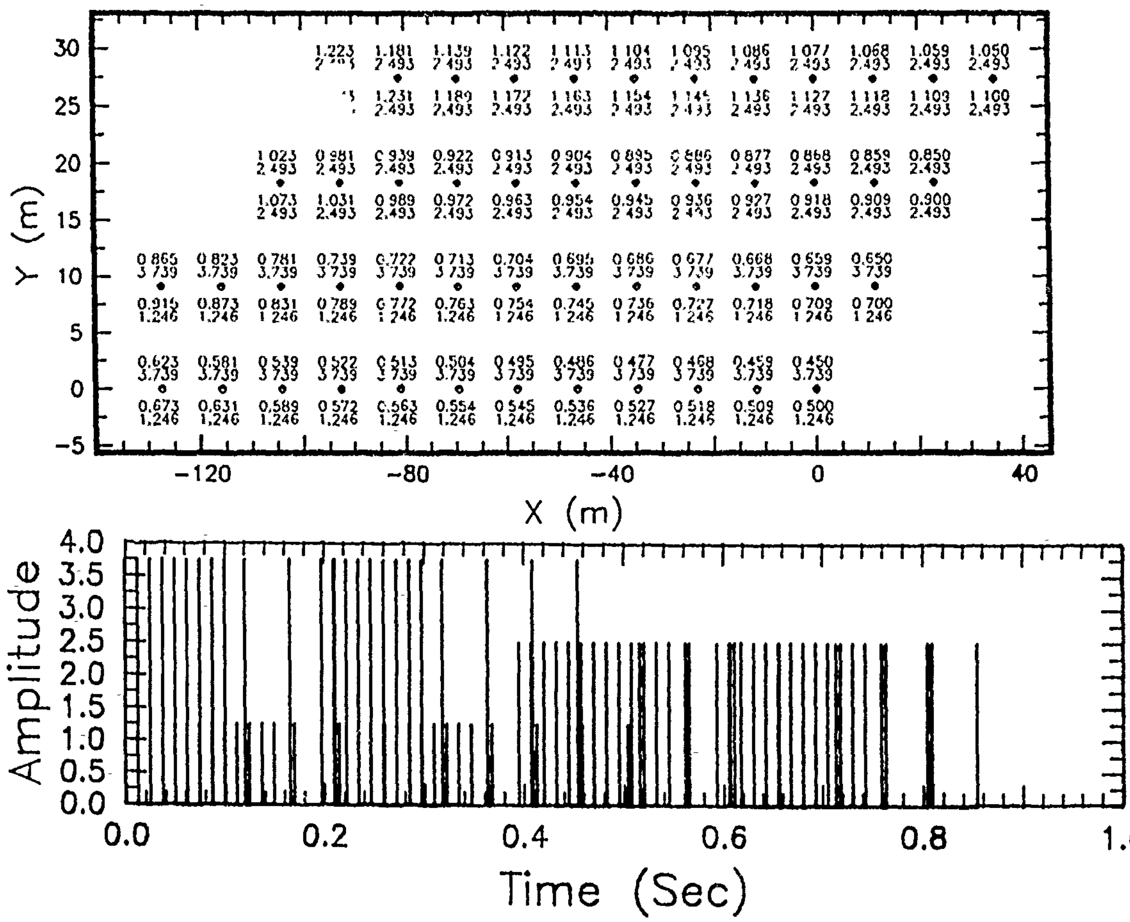


Figure 8: (Top) Charge pattern for Explosion 3 (plan view). Locations of each hole are indicated by small circles. Numbers above each circle indicate firing time (sec) of upper charge and charge weight (thousands of pounds), respectively. Numbers below circle refer to lower charge firing time and charge weight. (Bottom) Time series of Explosion 3, assuming station azimuth 115 deg and phase velocity 3000 m/sec. Amplitude is charge weight in thousands of pounds.

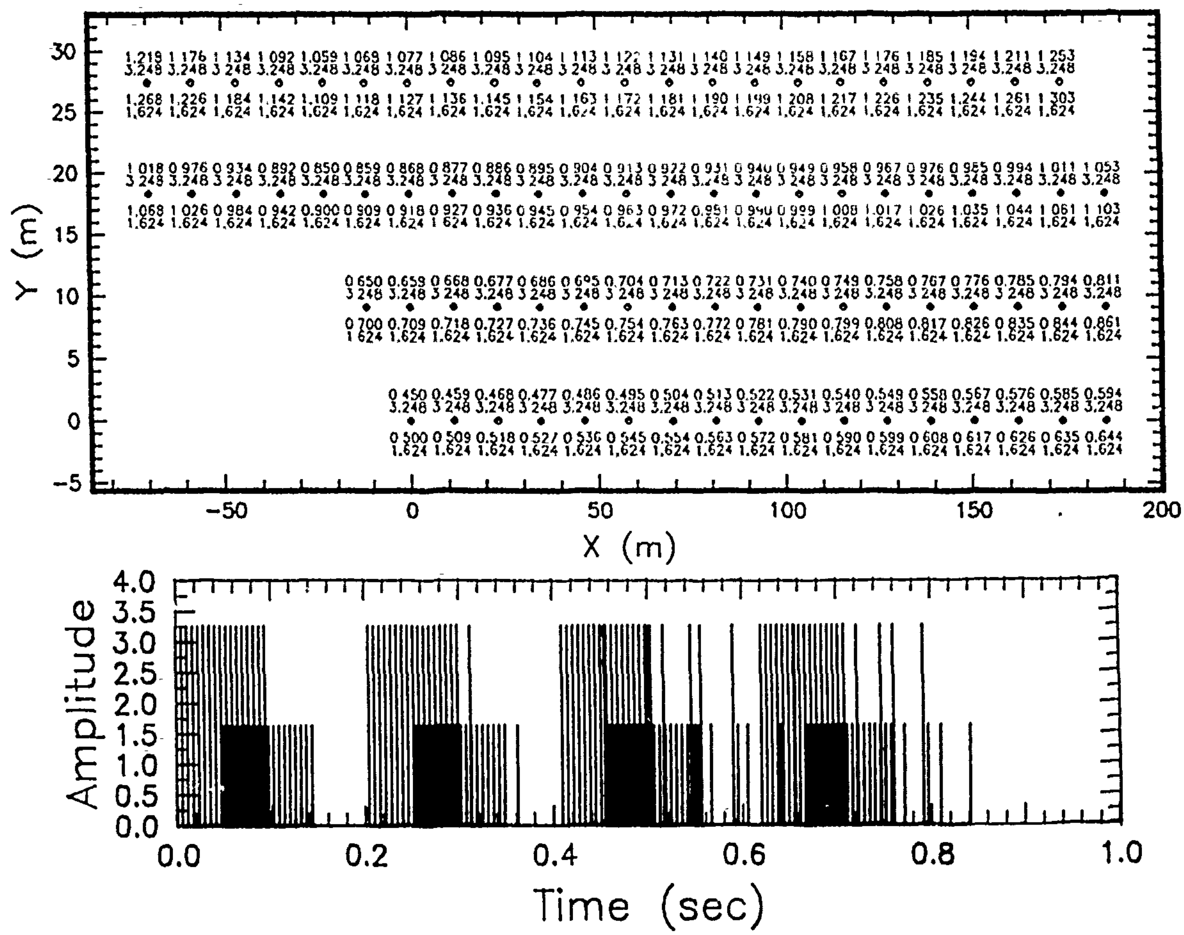


Figure 9: (Top) Charge pattern for Explosion 4 (plan view). Locations of each hole are indicated by small circles. Numbers above each circle indicate firing time (sec) of upper charge and charge weight (thousands of pounds), respectively. Numbers below circle refer to lower charge firing time and charge weight. (Bottom) Time series for Explosion 4, assuming station azimuth 125 deg and phase velocity 3000 m/sec. Amplitude is charge weight in thousands of pounds.

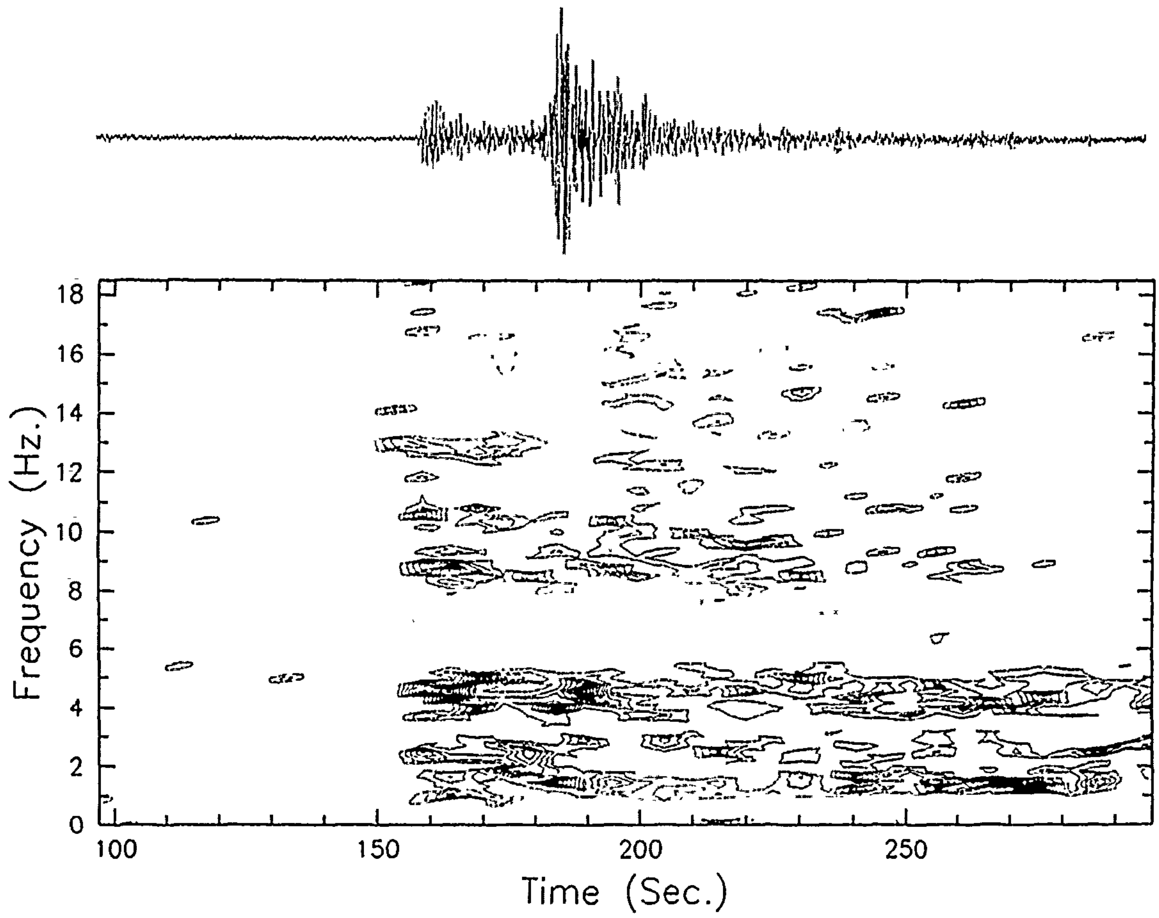


Figure 10: Time series (top) and sonogram (bottom) for Explosion 2.

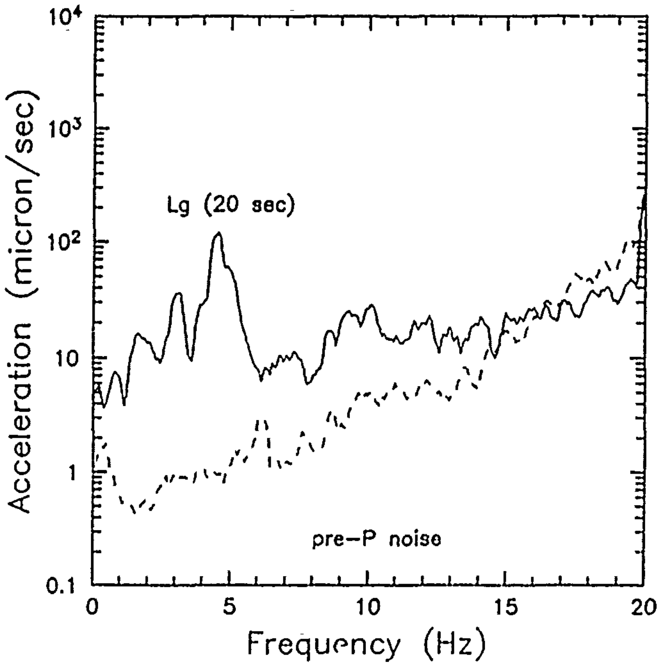


Figure 11: Vertical component Lg acceleration spectrum and pre-P wave noise amplitude spectrum for Explosion 1. Spectra were calculated using 20 second time windows and were smoothed using a 4 point moving average filter.

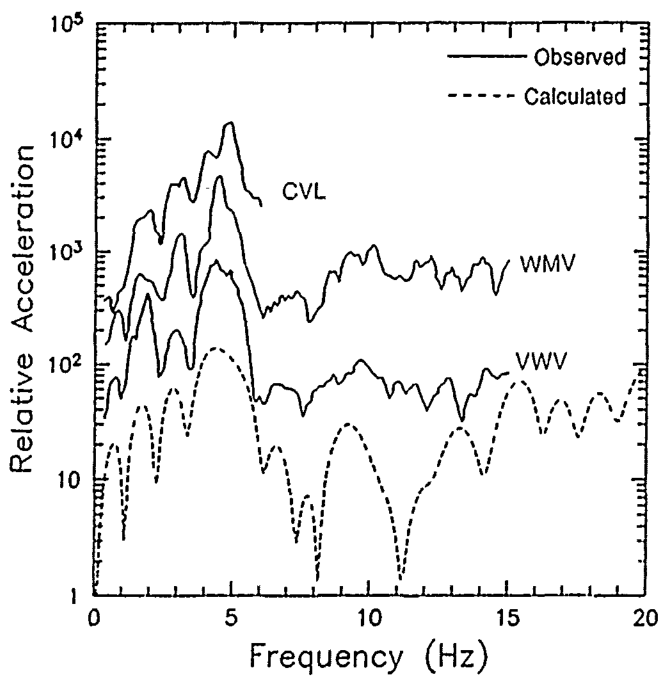


Figure 12: Solid lines show vertical component Lg acceleration spectra for Explosion 1 at stations CVL, WMV and VWV. Dashed line shows model spectrum. Amplitudes have been scaled to separate the spectra on the plot.

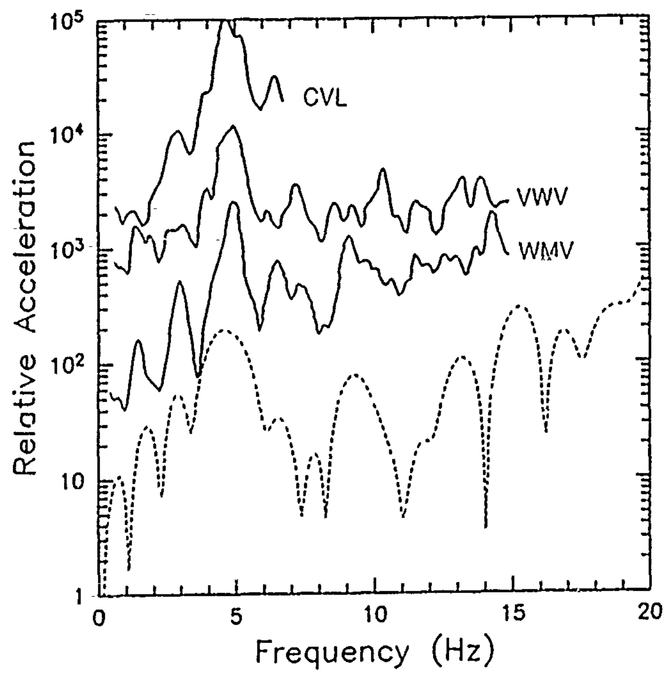


Figure 13: Solid lines show vertical component Pg acceleration spectra for Explosion 1, at stations CVL, VWV and WMV. Dashed line shows model spectrum. Amplitudes have been scaled to separate the spectra on the plot.

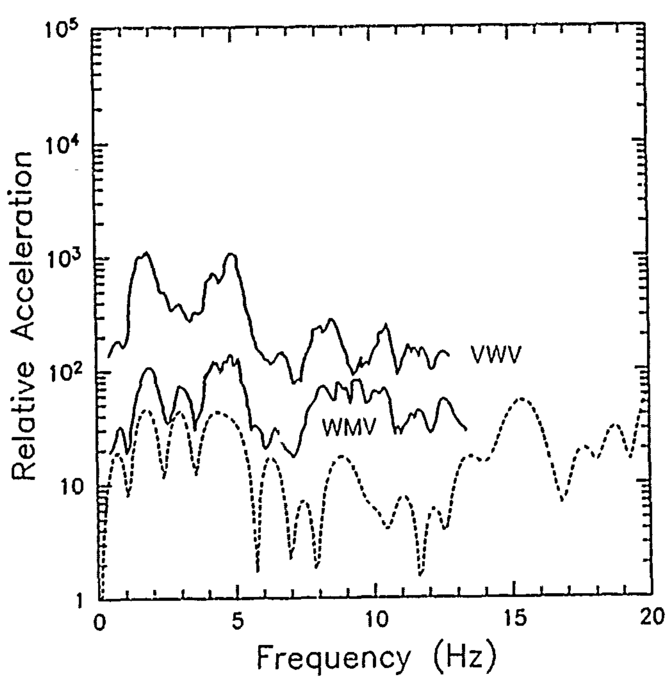


Figure 14: Solid lines show vertical component Lg acceleration spectra for Explosion 2, at stations VWV and WMV. Dashed line shows the model spectrum. Amplitudes have been scaled to separate the spectra on the plot.

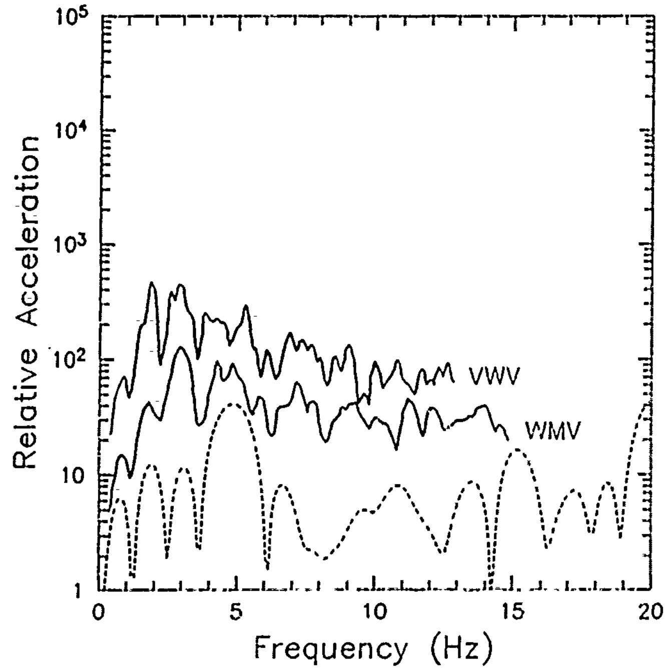


Figure 15: Solid lines show vertical component Lg acceleration spectra for Explosion 3, at stations VWV and WMV. Dashed line shows the model spectrum. Amplitudes have been scaled to separate the spectra on the plot.

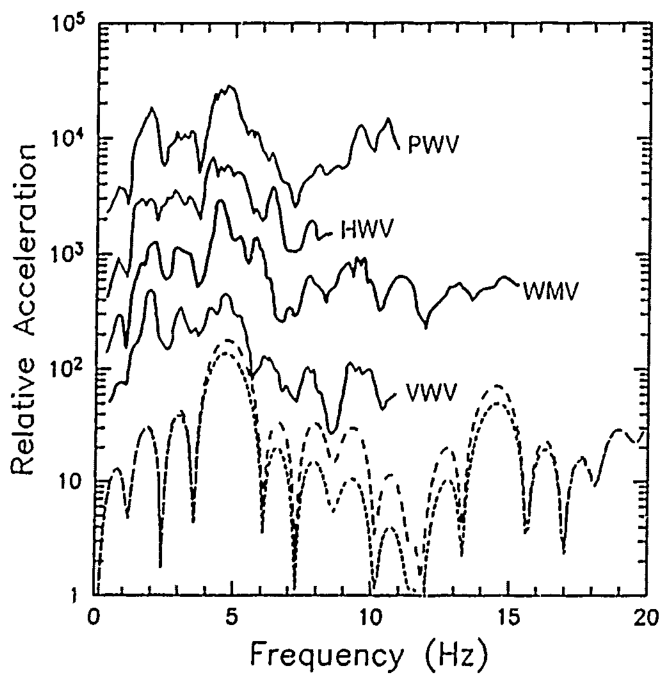


Figure 16: Solid lines show vertical component Lg acceleration spectra for Explosion 4, at stations PWV, HWV, WMV and VWV. Short dashed line shows the model spectrum, assuming that charges were decked. Long dashed line shows the model spectrum assuming that charges were not decked.

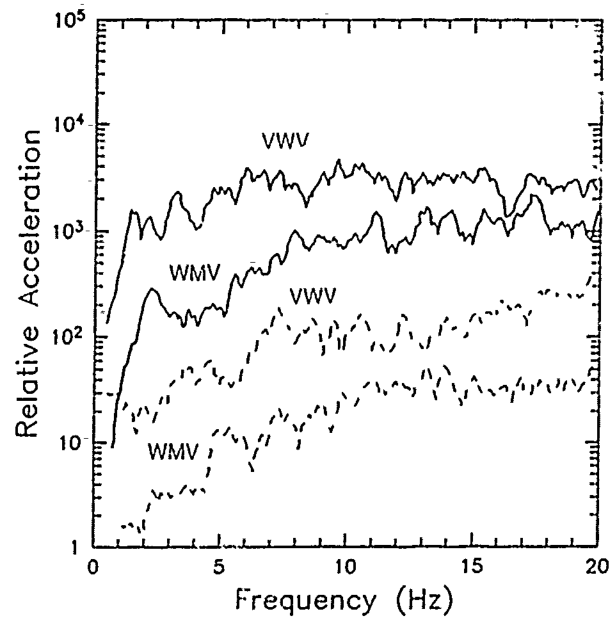


Figure 17: Solid lines show vertical component Lg acceleration spectra (unclipped) for the magnitude 3.5 Kentucky - Virginia border earthquake of November 27, 1987. Twenty second time windows were used, and the spectra were smoothed using a 4 point moving average filter. Dashed lines show the pre-P wave noise spectrum. The amplitudes have been scaled for separation on the plot: signal/noise ratios at the two stations are preserved.

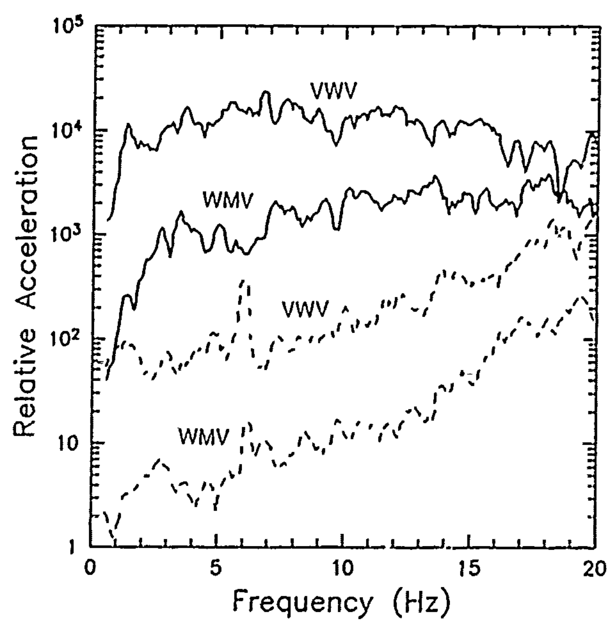


Figure 18: Solid lines show vertical component Lg acceleration spectra (unclipped) for the magnitude 4.0 Eastern Kentucky earthquake of August 17, 1990. Twenty second time windows were used and the spectra were smoothed using a 4 point moving average filter. Dashed lines show the pre-P wave noise spectrum. The amplitudes have been scaled for separation on the plot: signal/noise ratios at the two stations are preserved.

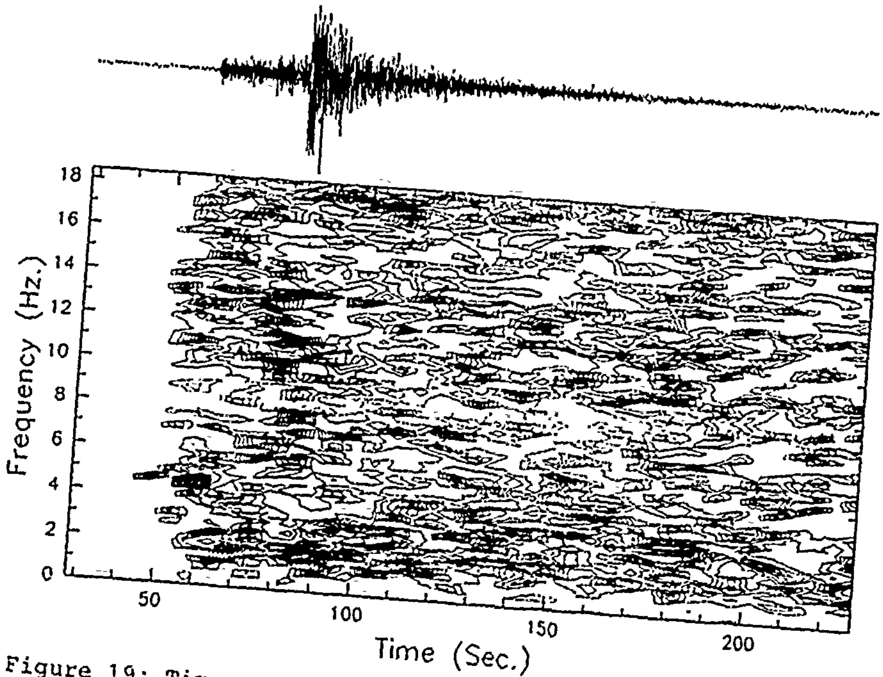


Figure 19: Time series (top) and sonogram (bottom) for the November 27, 1987 Kentucky - Virginia border earthquake.

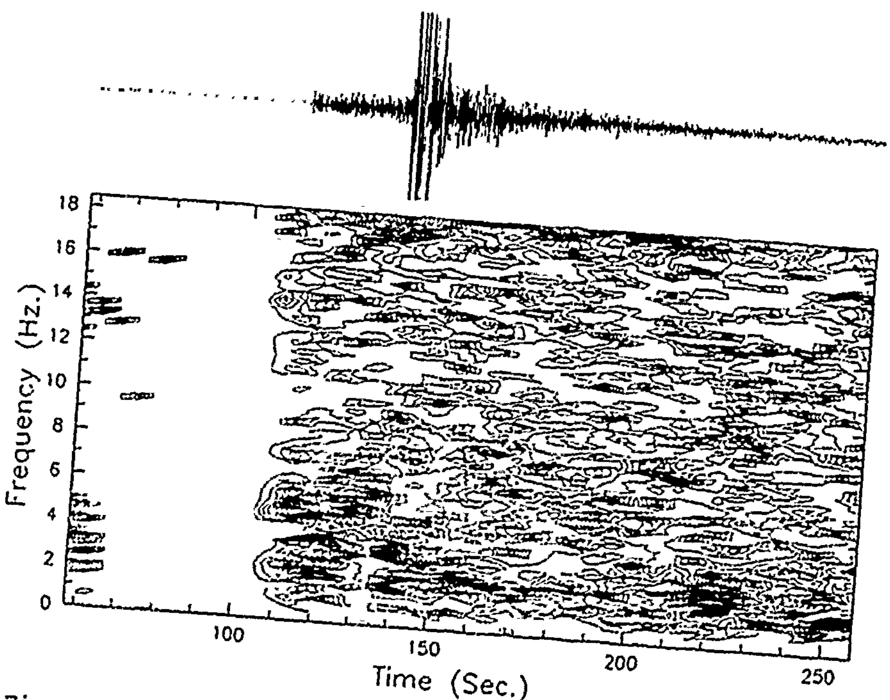


Figure 20: Time series (top) and sonogram (bottom) for the August 17, 1990 Eastern Kentucky earthquake.

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